JOURNAL OF CHEMICAL EDUCATION

pubs.acs.org/jchemeduc Article

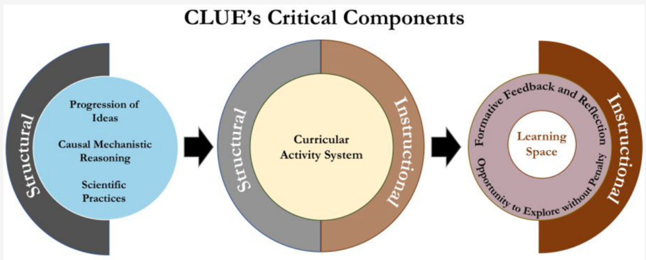
Components Critical to Successful Adoption and Adaptation of CLUE, a Transformed General Chemistry Curriculum

Sonia M. Underwood,* Alex T. Kararo, Lynmarie A. Posey, Amy M. Pollock, Deborah G. Herrington, Ryan L. Stowe, Justin H. Carmel, Michael W. Klymkowsky, and Melanie M. Cooper

Cite This: J. Chem. Educ. 2023, 100, 3374−3385 Read Online

ACCESS | Metrics & More | Article Recommendations | Supporting Information

ABSTRACT: It is generally accepted that if a course or curricular transformation is to be implemented with fidelity, the users must understand how and why the transformation is different from their current practices and which aspects of the transformation are essential to achieving comparable student learning outcomes. In this article, we provide a detailed description of how our research team used the Fidelity of Implementation (FOI) framework during a week-long workshop to identify five critical components of the transformed general chemistry curriculum *Chemistry, Life, the Universe and Everything* (CLUE): progressions of ideas, causal mechanistic reasoning, scientific practices, formative feedback and reflection, and the opportunity to explore without penalty. These components are connected through the curricular activity system, which are described in detail along with an explanation of how these components could be used for further propagation.



KEYWORDS: *General Public, First year undergraduate/general, Curriculum*

Downloaded via MICHIGAN STATE UNIV on November 10, 2023 at 15:32:28 (UTC).
See https://pubs.acs.org/sharingguidelines for options on how to legitimately share published articles.

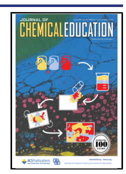
INTRODUCTION

Curricula should not be thought of as ready-made collections of materials to be handed to instructors and implemented with perfect fidelity to the original vision. Indeed, enacting a curriculum without modification is rare and is not necessarily desirable. Institutional contexts within which curricular resources were developed and tested may differ from adopters' institutional contexts in important ways—adaptations may be required for a curriculum to "work". Due to these factors, most modern scholars have moved beyond the binary view that instructors can either "follow or subvert" a curriculum to more nuanced theoretical frameworks in which educators can *draw on*, *interpret*, or *participate with* the materials they use.[1,2] It is the job of curricular designers, then, to support the community in adapting materials in principled ways that are likely to enhance efficacy.

Supporting principled adaptation of curricular resources demands that we shift from viewing curricula as monolithic, invariant collections of resources toward a model in which curricula are tool kits that can be used effectively in several ways. Roschelle refers to this sort of model as a "curricular activity system" and demonstrated that partnerships between researchers and practitioners can be an effective way to adapt resource systems to local contexts.[3−5] There is an intuitive appeal to viewing curricula as systems of resources that are both flexible and capable of supporting the desired learning outcomes. However, realizing functional curricular activity systems is more complex in practice than it might appear in theory. Designers must consider what components of an activity system are necessary and which can be omitted or substantially changed. They further need to work to embed features in materials that encourage adaptations in keeping with design principles undergirding these materials.[6] Finally, it is useful for potential adopters to engage with a community experienced in using the suite of curricular resources, so they can get feedback on the changes they are contemplating.

In the present work, we look across different enactments of the transformed general chemistry curriculum *Chemistry, Life, the Universe and Everything* (CLUE)[7] to consider both where this curricular activity system is flexible and, perhaps even more importantly, what components of the system are critical to its function. To assist us in this work, we leverage the Fidelity of Implementation (FOI) framework,[8,9] because it allows for a description of designers' intent, instructor knowledge useful for principled adaptation, and how an innovation is enacted in a context. As we will see, identification of CLUE's critical components (aspects that are essential to the structural and procedural/process pieces of an innovation) by reflecting on diverse enactments provides potential adopters

Received: March 7, 2023
Revised: August 15, 2023
Published: August 30, 2023



ACS Publications © 2023 American Chemical Society and Division of Chemical Education, Inc.

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

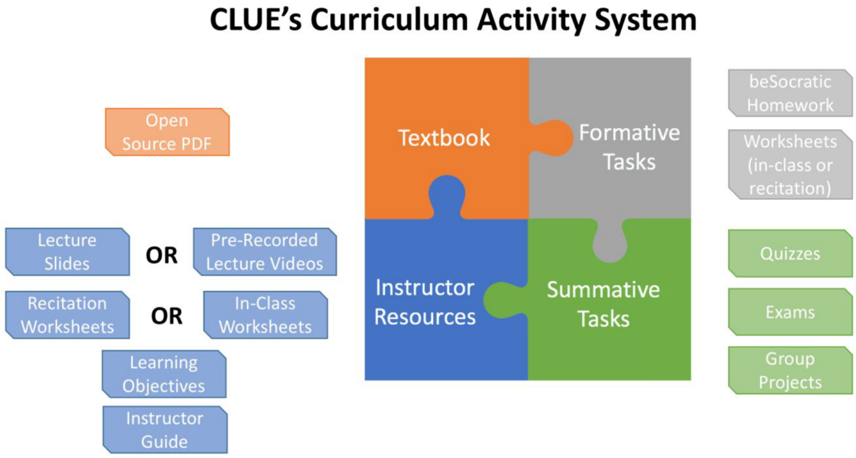


Figure 1. Curricular activity system for CLUE: textbook, instructor resources, formative tasks, and summative tasks.

with a better understanding of the essential aspects of the curriculum that are important for future implementations.

■ CHEMISTRY, LIFE, THE UNIVERSE AND EVERYTHING (CLUE)

Chemistry, Life, the Universe and Everything (CLUE) is a two-semester theory and evidence-based transformed general chemistry curriculum designed to support students as they build and use knowledge over time.[7] The curriculum centers around four core ideas (i.e., *electrostatic and bonding interactions*, *atomic/molecular structure and properties*, *energy*, and *change and stability in chemical systems*[11,12]) progressively built upon throughout the course, starting with simple phenomena (e.g., two noble gas atoms attracting each other) to complex systems (e.g., networked biological reactions, such as the impact of increasing CO_2 levels on blood pH). The goal of this curriculum is to help students construct a more expertlike framework of knowledge that can be used to explain and predict chemical phenomena.

The CLUE curriculum has been taught by multiple instructors at a range of institutional types, including private and public liberal arts colleges, large R1 universities, and community colleges.[13] A variety of instructional approaches have been employed, ranging from a large-enrollment lecture with an additional mandatory recitation section to an active learning approach in which students work on group worksheet activities during class time. Class sizes have ranged from over 400 students to fewer than 20.[13] These different settings and student populations have necessitated somewhat different implementations of CLUE, with the goal of keeping the overall research-based curricular design of the course intact. Looking across CLUE enactments in these different environments, let us consider what components of the curriculum are critical to its function and where flexibility exists for principled adaptations. Identifying and unpacking these critical components will provide better support for effective adoption, adaptation, and propagation of the CLUE curriculum. Further, other curriculum developers may adopt this approach to clarify what is important for their own curricular innovations.

■ CURRICULAR ACTIVITY SYSTEM FOR CLUE

Anderson et al. state "a curricular activity system includes components such as teacher guides, student guides, professional development designs, and formative and summative assessments that fit together to comprise a shared vision for teaching and learning" (p. 1029).[14] Therefore, for CLUE, all of the parts of the curricular activity system are crucial for implementation; however, within each part, instructors may choose particular aspects depending on the institution and students. The curricular materials for CLUE (Figure 1) consist of four parts: 1) the textbook – an open educational resource written for the student to explain the chemistry and why it is important,[15] 2) instructor resources – PowerPoint slides for classroom instruction or prerecorded lecture videos, worksheets that can be used either in class or for recitation activities, learning objectives/performance expectations, and an instructor guide, 3) formative tasks – that may consist of the worksheets for in-class or recitation activities, and the homework activities, and 4) summative tasks – exams, quizzes, and/or group projects.

All of these parts work together to make up the curriculum and assist faculty in implementing CLUE. Implementation of the curricular activity system requires support for faculty so that they understand how the parts integrate with each other to support student learning and how they can be adapted for particular situations. For example: a large lecture course might use lecture PowerPoints, homework, group recitation worksheets, and summative assessment items. However, a smaller class or a classroom set up for group interactions might use short video lectures and group activities in place of lectures and recitations. The key point is that all the materials are integrated[16] and all of the parts are necessary. That is, the class materials, homework, and assessments are all aligned in a way that helps students perceive the connections (unlike commercial homework systems).

■ TEAM: PARTICIPANTS

To support reflection on CLUE critical components and opportunities for principled adaptation, we captured a range of perspectives from participants who were familiar with the design of the CLUE curriculum and had expertise in implementing it in various educational environments. The expertise of the team included perspectives on 1) design and development of the curriculum, 2) expansion of the curriculum to other faculty and other institutions, and 3) design and development of additional related courses beyond the general chemistry series.

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

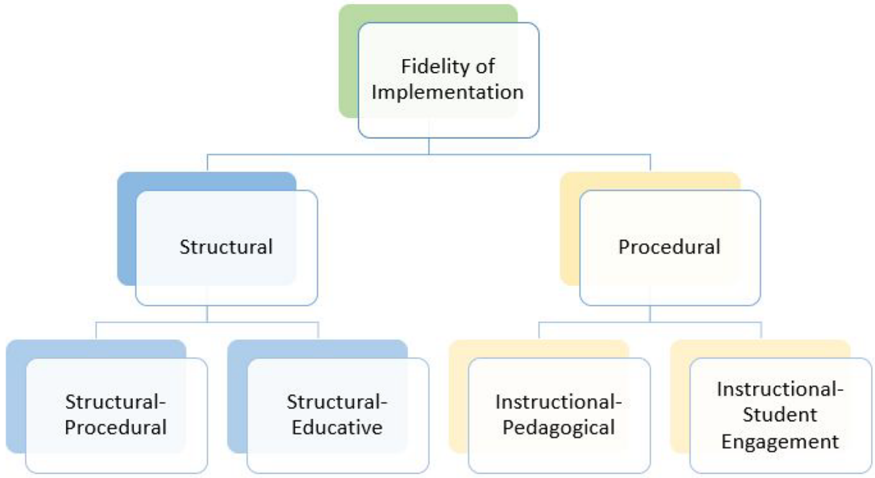


Figure 2. Organization of the Fidelity of Implementation (FOI) framework[8]

When considering components fundamental to a curriculum, as well as what principled adaptations could look like, it is necessary to consider how and why developers constructed the curriculum as they did. Author M.M.C., a researcher in chemical education, has taught the CLUE curriculum for multiple years at two institutions and used a Design-Based Research approach[17] to conduct research that informed modifications to the curriculum to improve its effectiveness. Author M.W.K. is a researcher in molecular, cellular, and developmental biology and has designed and taught introductory molecular biology courses.[18] Together these two authors developed the text for the course, which was then extended, initially by M.M.C. and then further by A.M.P. and S.M.U., to a broader range of instructional materials, including lecture and class presentation materials, formative assessments such as homework tasks, group activities, and summative examinations.

The next set of team members were early adopters of CLUE who were not involved in initial development efforts. They include faculty who worked to expand the CLUE implementation at the developer's institution (Michigan State University – MSU) and across other institutions. These participants provided important information about how nonauthors adopted and adapted the curriculum, as well as the supports needed and challenges encountered when implementing the transformed curriculum. Author A.M.P. is the director of general chemistry at MSU and has led the expansion of CLUE within MSU over the last 10 years to include 11 instructors, including authors L.A.P. and D.G.H. CLUE enactments at MSU currently impact over 5,000 students each year. Author S.M.U. has adapted the CLUE curriculum into an active learning setting at Florida International University (FIU), which has now further expanded to involve 6 instructors (including author J.H.C.) to impact about 2,000 students per year. Authors S.M.U. and A.T.K. have to date provided support for 60 instructors at 15 additional institutions outside of MSU and FIU (including private, public, and both small and large institutions) to adapt and implement the curriculum.

Finally, faculty who worked to adapt the CLUE curriculum to develop approaches to both high school (authors D.G.H. and R.L.S.) and preparatory courses (author L.A.P.) were also included on this team. They provided insight into how the CLUE approach to chemistry instruction could inform the design of courses that precede general chemistry. The two-semester organic chemistry sequence (*Organic Chemistry, Life, the Universe and Everything* – OCLUE[19]) was also created by the developers of CLUE (authors M.M.C. and M.W.K.) and currently impacts between 600 and 1,000 students yearly at MSU. This work showcases how lessons learned from CLUE can inform the design of subsequent courses.

Aside from M.W.K., all authors in this article have taught or observed versions of the CLUE curriculum in its entirety. The diversity of expertise within the team allowed us to look at the curriculum from different perspectives, which we believe helped us characterize the critical components independent of the instructional methods or the institutional setting. Further, diverse experiences enacting or observing CLUE in different contexts enabled the team to comment on where the curricular activity system is flexible to principled adaptation.

METHODS USED TO IDENTIFY CRITICAL COMPONENTS FOR CLUE

Fidelity of Implementation Framework as a Guide

Our team elected to make use of the FOI framework[8,9] to describe CLUE critical components and opportunities for principled adaptation. This framework is a useful lens since it encompasses all aspects for the implementation of an innovation from the designer's intent to what the instructor must know (both the "what" and "why") to how the innovation is implemented by the instructor and how students engage with the curriculum (the "how"). Attending to how critical components are realized across contexts supports inferences regarding which parts of a curricular activity system should be enacted without modification and which can be changed while maintaining (or enhancing) innovation efficacy.

The general FOI framework[8,9] consists of two main categories, as shown in Figure 2. The structural category characterizes the **knowledge** an instructor needs in order to implement an innovation, which includes the curriculum designer's intent regarding what the instructor should do (*structural-procedural* subcategory) and the bodies of knowledge the instructor must possess in order to implement the curriculum effectively (*structural-educative* subcategory). Note that when we say "effectively" here, we mean "supportive of students constructing an interconnected and useful understanding of chemistry". We do not necessarily mean that effective enactments are carbon copies of the developers'

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

enactments. Indeed, figuring out where CLUE materials are flexible to adaptation is an important part of the present work. The process category of FOI involves describing **how** the instructor implements the curriculum, which involves the expectations related to the instructor's interactions with the students (*instructional-pedagogical* subcategory) and the expectations for the students' interactions with the instructor, their peers, and the curriculum materials (*instructional-student engagement* subcategory).

While the FOI literature has been growing in recent years, there is still an under-representation of work reflecting on FOI as it relates to the propagation of innovations, especially curricular innovations.[20] Within the FOI literature, there have been different methods used to measure FOI. Some have looked at levels of variation between the developed innovation and the adapted innovation,[21] while others assessed the use of each feature of the innovation,[22,23] even assigning each critical component a composite score.[9] The extant literature also tends to focus on the fidelity of the implementation of instructional strategies rather than full curricular transformations. For example, Stains and Vickrey[8] identified and characterized the critical components of peer instruction using previously published literature, while Collison et al.[24] developed an observational protocol to measure the fidelity of implementation of guided inquiry materials in an organic chemistry lab across instructors and institutions. In this report, we use the FOI framework to describe enactments of a fully transformed curriculum, including assessments and organization of content in addition to teaching methods.

Using the FOI framework as a guide during Summer 2019, the project team collected two main sources of information to describe the critical components of the CLUE curriculum: 1) a survey developed by authors S.M.U. and A.T.K. to collect feedback and ideas from each team member and 2) a week-long summer workshop in which the whole team came together to discuss the preliminary ideas from the survey and synthesize them into the critical components.

First Step − Survey

The open-ended survey consisted of four sections, one for each category of the FOI framework (structural-procedural, structural-educative, instructional-pedagogical, and instructional-student engagement), and was administered through *Qualtrics* prior to the summer workshop. The full survey is provided in the Supporting Information.

Each section of the survey provided the definition of the category from the FOI framework followed by two to three questions to elicit the respondent's ideas about the critical components for that category. For example, in the *structural-procedural* category, the team members were provided the following prompt: "This category describes how the curriculum is intended to be implemented focusing on procedural and organizational features. Examples of structural-procedural could include order of instructional elements and nature of intervention materials. Keep this definition in mind when answering the following questions." and then were asked: 1) Describe the essential features of CLUE that a new instructor must understand in order to teach CLUE (i.e., what makes CLUE "CLUE"?), 2) How should the new instructor teach CLUE?, and 3) What instructional materials should the new instructor use to teach CLUE? Results from the survey were compiled to provide information for the broader workshop team.

Second Step − Workshop

The goals of the week-long summer workshop were to 1) identify and define the critical components of CLUE, 2) recommend how the critical components should be implemented by future adopters, and 3) recommend how the critical components and their fidelity might be assessed or characterized. These aspects were all reviewed and discussed by the team, until consensus was reached.

The workshop took place over five consecutive days during Summer 2019 and was facilitated in person at MSU by authors S.M.U. and A.T.K. The rest of the team members were either present in person or virtually via Zoom, and although some may have missed parts of the workshop due to their schedules, materials and summaries of the discussion were made available to all. Morning sessions involved the entire team, while afternoon debriefing sessions consisted of only authors S.M.U. and A.T.K., who synthesized the day's session and prepared for the next morning's session. A summary of progress was emailed to the entire team each day along with plans for the next day, links to relevant documents such as literature on the FOI framework, and all working documents created during the workshop. A detailed description of the activities that occurred each day for the workshop is provided in the Supporting Information.

Day 1 of the workshop series began with an overview of the FOI framework and a discussion of the importance of identifying and describing critical components to assist with propagating a curriculum. Discussion first centered around why the FOI framework was chosen, what critical components are involved, and what they might look like in a curriculum. This last element was crucial since much of the literature focuses on propagation of evidence-based teaching strategies (how we teach) rather than the curriculum (what we teach and why). Using the findings from the individual survey responses as a guide (see Supporting Information for common codes from the survey data), the team continued during the week, through discussion and consensus building, to identify and describe the critical components within each of the FOI subcategories, resulting in a set of critical components. For each critical component, the team developed a definition, an example, implementation recommendations, and guidance on how to assess or characterize the component. Drawing from their diverse experiences, the project team unpacked different ways each critical component might be enacted while maintaining (or enhancing) the efficacy of CLUE.

■ ADAPTING THE FOI FRAMEWORK TO FIT CURRICULAR NEEDS

During discussions among the team, it became clear that the subcategories from the original FOI framework[8,9,20] (*structural-procedural, structural-educative, instructional-pedagogical, instructional-student engagement*) were too fine a grain size for our purposes, making it difficult to place each critical component into a particular subcategory. Instead, the critical components of the curriculum fit better within the larger categories of the FOI framework, where the structural category represented the "what" and "why" of the curriculum and the instructional category represented the "how" of the curriculum.

The team identified five critical components for the CLUE curriculum (Box 1): three of which fit into the *structural* category ("what" and "why" of innovation) and two fit into the *instructional* category ("how" of innovation). It also became

Box 1. Critical Components for CLUE

1. Progressions of ideas
2. Causal mechanistic reasoning
3. Scientific practices
4. Opportunity to explore without penalty
5. Formative feedback and reflection

clear that a unique aspect when applying FOI to curricular innovation compared to prior work with EBIPs is that these categories alone do not let us describe useful curricular enactments. That is, for the CLUE curriculum, we found that the structural critical components need to be embodied in a suite of materials (i.e., curricular activity system[3,14]) and thus enacted in certain ways through the instructional critical components to support the learning as intended. Essentially, the curricular activity system is a vital aspect of the curriculum that allows instructors to bridge the structural and instructional critical components in a useful way (Figure 3). In the following sections, we discuss each of the critical components in Box 1 in further detail.

■ CRITICAL COMPONENTS FOR THE CLUE CURRICULUM

Here we discuss each critical component of CLUE and provide where appropriate: 1) a definition, 2) an example, 3) an implementation strategy, 4) a strategy to assess student understanding, and 5) a strategy to characterize the fidelity of implementation. It is important to note that not all of these are appropriate for each critical component, as is explained below where applicable.

Structural Category

As noted earlier, the structural category of the FOI framework[8,9,20] refers to the knowledge the instructor would need to enact the curriculum with fidelity. The three critical components that emerged from our work are progressions of ideas, causal mechanistic reasoning, and scientific practices. Each of these components is intended to work together to support students in making deeper connections as they learn to use their knowledge.

Progressions of Ideas. *Definition.* The CLUE curriculum was developed as a series of interconnected progressions of ideas[7] that incorporate and connect four chemistry core ideas[11,12] (i.e., what we want students to know): *electrostatic and bonding interactions, atomic/molecular structure and properties, change and stability in chemical systems*, and *energy*. As the course sequence progresses, these core ideas build upon one another in increasing sophistication and are interconnected throughout the curriculum to explain phenomena. At every stage, individual topics are connected to these core ideas, with the intention of helping students develop a robust and connected cognitive framework, rather than a set of disconnected ideas.[25]

Example. In the first semester of the two-semester course, the core idea of *electrostatic and bonding interactions* begins with the phenomenon that noble gases can form liquids and solids. Students are guided through constructing models and explanations for how nonpolar monatomic gases, such as argon or xenon, can attract each other to form liquids and solids via London dispersion forces using a simplified model of the atom. As the semester progresses and more complex models of the atom are introduced as needed to account for additional spectroscopic evidence, the same core idea is further developed to explain periodic trends (via the concept of effective nuclear charge), covalent bonding, dipole−dipole, and hydrogen bonding interactions, and differences in melting or boiling points between substances arising from differences in the strength of intermolecular interactions. In the second semester, explicit incorporation of the core idea of *electrostatic and bonding interactions* continues with discussions of more complex phenomena such as solubility, acid−base reactions, and eventually, simple organic nucleophilic substitutions. This approach is continued in the organic chemistry curriculum *Organic Chemistry, Life, the Universe, and Everything* (OCLUE),[19] beginning with a more thorough introduction to acid−base chemistry, which then serves as the basis for the subsequent curriculum, that takes a mechanistic approach toward organic chemistry. Most of the curriculum can be considered by extending the lens of acids and bases from Bronsted to Lewis and through to electrophiles and nucleophiles.

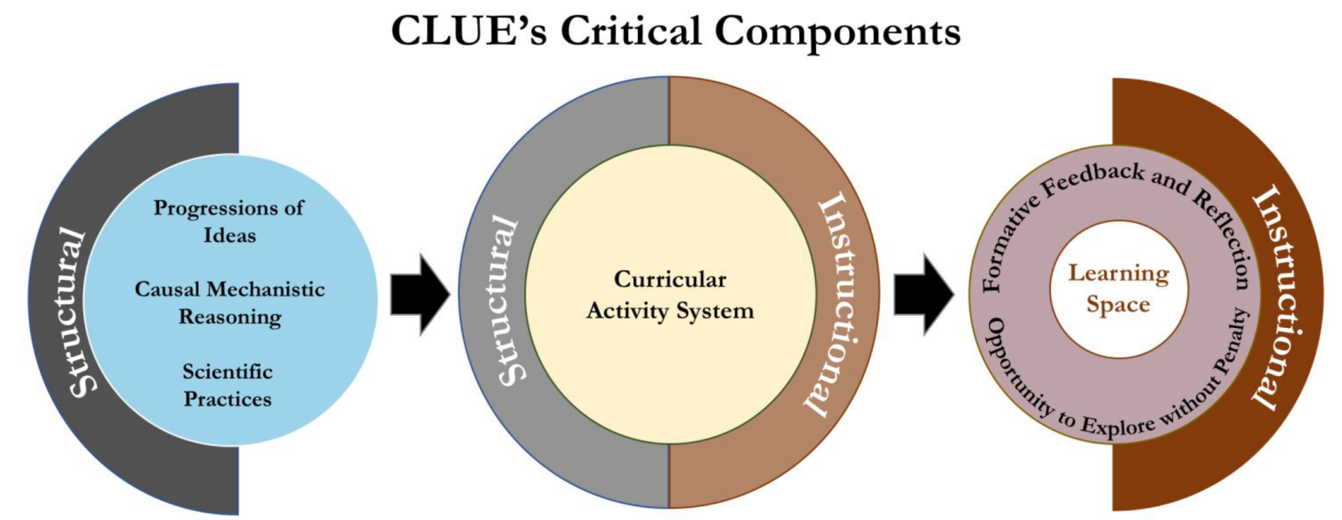


Figure 3. Relationship between the CLUE structural and instructional critical components bridged by the curricular activity system

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

Within the CLUE curriculum, each core idea is woven throughout the curriculum in a similar way. That is, these ideas are not treated separately, but as the curriculum progresses, each core idea is developed further and used with other core ideas to explain more sophisticated phenomena, concluding with a discussion of networks of reactions, as found in biological systems. A fuller description of the progressions can be found in the original curriculum design paper by Cooper and Klymkowsky.[7]

Implementation of the Progressions of Ideas. When faculty implement the curriculum, obviously they will be operating with different constraints and needs (e.g., semester vs quarter systems, different class time periods, demands that other content must be included, or disruptions from natural disasters), which may require decisions about how to modify the curriculum. However, successful adopters of the curriculum need to understand how the progression of ideas is integrated throughout. That is, for faculty to modify the curriculum in principled ways, they should first understand ***how and why*** the sequence is designed to build upon previous ideas. If the material is omitted, it may be essential for a subsequent topic, which could cause problems later. Similarly, if material is added, faculty should think carefully about where it should be placed and how to connect it with the existing progression of ideas. Faculty development materials should emphasize why the curriculum flows in the way that it does so that adopters understand how to maximize the impact of the curriculum and how switching major parts of the curriculum (as is often encouraged by publishers for commercial texts) could cause problems later in the course.

With the aid of adopters from 15 institutions outside of the developer's institutions, a series of resources have been developed and made available for faculty who plan to implement the CLUE curriculum,[13] including suggestions for places where worksheets or content could be modified, omitted or added and how this could be achieved. An example of an approach that can assist faculty with timing and external constraints is to develop short lecture videos for students to watch and interact with (through embedded questions) outside of class time, so that class time can be available for engaging students in building and connecting ideas to construct knowledge.

Assessment of Student Engagement with Progressions of Ideas. While it is not feasible to assess the extent to which a core idea progression supports useful chemistry learning while a CLUE enactment is in-progress, it is possible to collect multiple pieces of evidence from tasks at various stages of the curriculum to characterize how students' knowledge is developing. For example, the team has designed tasks to help characterize student use of core ideas to explain a range of phenomena, including London dispersion forces, boiling point trends, and acid−base reactions that can be used to assess the core idea *electrostatic and bonding interactions* at various stages of the course.[26−29]

Characterizing the Fidelity of Implementation for the Progressions of Ideas. The ways that faculty adopt and adapt the course materials (e.g., lecture slides, in-class worksheets, homework, and assessment items) to fit their own needs can provide an approach to characterizing fidelity. The changes made can be classified as 1) the materials were used as provided, 2) the materials provided were used with minor modifications, 3) significant changes were made that did not impact the overall progressions, and 4) significant changes to the materials were made in which important parts of curriculum were lost, through omission or rearrangement of the curriculum, that are important to learning progression.

Causal Mechanistic Reasoning. *Definition.* Mechanistic reasoning can be considered as an "epistemic heuristic",[30] a general strategy to make sense of phenomena that students might use to construct an explanation. Supporting students to construct such explanations helps them understand the "rules of the game" and is crucial for all students, but particularly for students who have had fewer opportunities to learn how science is done. Indeed, Ralph and colleagues have shown, using data from CLUE examinations, that assessment tasks that emphasize mechanistic reasoning tend to be more equitable than traditional general chemistry assessments tasks that emphasize numerical problem solving alone.[31]

Causal mechanistic explanations combine the scientific practices of constructing explanations (or using models) with the crosscutting concept of cause and effect to explain both how and why a phenomenon occurs. Constructing such an explanation requires that students engage in causal mechanistic reasoning, and several researchers have provided ways to define it. For example, Russ et al.'s discussion concludes that "*mechanistic reasoning involves describing how the particular components of a system give rise to its behavior*",[32] and Krist and colleagues expand on this idea to emphasize that the components of the system are at least one scalar level below the phenomenon.[30] For example, the behavior of molecules as they interact can only be explained by considering the arrangements and interactions of electrons (a scalar level below).

Example. Building upon the same core idea of *electrostatic and bonding interactions*, students may learn that nonpolar molecules can stick together, or that many reactions involve an attraction of positive and negative parts of molecules, but if they do not understand how this charge separation occurs—and how and why such interactions are integral to increasingly complex phenomena - then they will not be able to apply these ideas in unfamiliar systems.[27,33−35]

Implementation of Mechanistic Reasoning (Ideally vs Enacted). Seeing mechanistic reasoning as a useful epistemic heuristic requires that students have multiple opportunities over time to practice with in-class or recitation group activities and receive feedback through both formative and summative assessments. Certainly, at least initially, students will need a great deal of support when constructing mechanistic explanations, which could be accomplished through coconstruction between instructor and students or by being provided with contextual feedback on formative assessments. The powerful influence of instructional and assessment emphasis on students' mechanistic reasoning was demonstrated by Ralph et al., who compared responses from students at different institutions on a task about how and why a solute dissolves in a solvent.[36] They found that while all instructors agreed that the topic had been "covered" in their general chemistry courses, students from the CLUE curriculum were more likely to construct mechanistic responses invoking energy and interaction ideas than students from an active learning environment or a didactic environment using a more traditional curriculum.

Assessment of Student Engagement in Mechanistic Reasoning. A number of researchers have proposed approaches to characterizing mechanistic reasoning. For example, Talanquer[37] used an approach that involves characterization of system components (e.g., entities, proper-

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

ties, activities, organization) and the types of reasoning (i.e., descriptive, relational, simple causal, and emerging mechanistic). Caspari and co-workers proposed a different framework guided by philosophies of science that involves identifying structural and energetic accounts as well as static and dynamic approaches to change.[38] In our work, we have emphasized the idea that a causal mechanistic explanation will provide both the *how* and the *why* of a particular phenomenon.[27] For example, a causal mechanistic explanation for why krypton atoms attract would include the idea that electron density fluctuates, producing a temporary dipole (how), which then results in an attraction between unlike charges (why).[26,39] We have found it productive to ask for separate answers for how and why, thus making it clearer that we are asking for more than a description.[27] We have also found it helpful to provide students with multiple drawing boxes to prompt the idea that a particular phenomenon is a process, not a static event.[26]

Characterizing the Fidelity of Implementation of Mechanistic Reasoning. One approach to determining the extent of mechanistic reasoning implementation is by characterizing the intellectual work emphasized and rewarded on formative and summative assessments. This can be accomplished by using the 3D-LAP,[11] a protocol specifically designed to allow researchers and practitioners to characterize assessments to identify the potential for students to integrate core ideas, scientific practices, and crosscutting concepts. An analysis of the frequency with which students engage in tasks that require causal mechanistic reasoning would also provide valuable information. It would be illustrative to find out whether such tasks were administered on a single worksheet or exam or whether they are routinely administered across formative and summative assessments, where various core ideas are invoked. We expect CLUE enactments that effectively support mechanistic reasoning will place substantial emphasis on this sort of intellectual work on high- and low-stake assessments throughout the course. That said, there are many ways this could be done—different phenomena, core ideas, entities etc. could be emphasized in different enactments.

Scientific Practices. *Definition.* Scientific practices are the way scientists investigate the world. The *Framework for K-12 Education*[25] describes eight scientific and engineering practices: asking questions (for science) and defining problems (for engineering), developing and using models, planning and carrying out investigations, analyzing and interpreting data, using mathematics and computational thinking, constructing explanations (for science) and designing solutions (for engineering), engaging in argument from evidence, and obtaining, evaluating, and communicating information.

Example. The scientific practices provide students with a way to use their knowledge rather than to merely restate facts and definitions or engage with disconnected skills. For example, drawing chemical structures is an important skill, but if not accompanied by building an understanding of how to use drawn structures to predict and explain chemical properties, drawing such structures becomes a disconnected task with no meaning.[40,41] If we can support students to understand the implicit information encoded within structures, then these structures can be used as *models* to predict and explain the properties of substances.[29,40] Instruction can target the scientific practice of *developing and using models*, which in conjunction with core ideas such as *electrostatic and bonding interactions*, *energy*, and *atomic/molecular structure and properties* allows students to explain a wide range of phenomena, from boiling point trends to nucleophilic substitution reactions.

For example, by focusing on the use of Lewis structures as models that can be used to predict and explain, we showed that CLUE students are more likely to draw accurate structures,[42] use them to predict properties,[43] and explain and predict the outcomes of acid−base reactions[34] than matched cohorts of traditionally taught students.

Implementation of Scientific Practices (Ideal vs Enacted). It is important to provide multiple opportunities for students to engage in scientific practices. We recommend that instruction should involve scientific practices including *mathematical and computational thinking, analysis and interpretation of data, developing and using models, and constructing explanations and arguments*. This engagement may take place in a wide range of settings, from small group activities in a large lecture class to recitations to active learning environments as well as individual homework assignments. Scientific practices should also make up a major component of formative and summative course assessments, whether those are graded for correctness or are rewarded for effort.

Assessment of Student Engagement in Scientific Practices. The critical components of scientific practices can be assessed through open-ended and multiple-choice assessment tasks. Examples of such assessment questions that present students with the opportunity to engage in scientific practices have been published previously.[44] For the examples described above, students could be asked to draw a Lewis structure and then use it to predict the types of reactivity that would be expected (*developing and using models*). Alternatively, students can be provided with a reaction and then asked to explain both how and why the reaction proceeds,[27] with particular emphasis on the way the structures can be used to predict such reactivity (through *developing and using models* and/or *constructing explanations*). Another example might ask students to calculate the percent ionization of a weak acid and then rerepresent the result of the calculation by drawing a molecular-level diagram of the aqueous solution (*using math and computational thinking*) and then explain how and why the structure of the given compound gives rise to its acidity (through *developing and using models* and/or *constructing explanations*).

Characterizing the Fidelity of Implementation for Scientific Practices. The fidelity of implementation of the scientific practices can also be characterized by using the 3D-LAP[11] to determine the percentage of assessment items that provide an opportunity for students to engage in the scientific practices. Classroom instruction can also be characterized using the *Three-Dimensional Learning Observation Protocol* (3D-LOP),[45] by recording the class and coding for the presence of scientific practices in the work of instructors and students during instruction. These measures could be compared to prior findings, which have shown that about half of the assessment points in the CLUE curriculum are three-dimensional (include core idea, scientific practice, and crosscutting concept), whereas in more traditional courses almost none of the items on an exam have the potential to elicit evidence of engagement in a scientific practice.[46]

Instructional Category

The instructional category of the original FOI framework[8,9,20] is concerned with **how** the innovation should be implemented. The intent of the CLUE curriculum is to create an inclusive

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

and equitable learning environment for students (Figure 3). After extensive discussion and analysis, we concluded that there are two critical components of CLUE that work together to support this goal: the opportunity to *explore without penalty* and *formative feedback and reflection*. We should note here that we do not specifically discuss what has come to be known as Evidence-Based Instructional Practices (EBIPs), since while those are important, much has been written about such strategies and their implementation.[47−49] Here we are concerned with critical components that are specific to the CLUE curriculum, while at the same time acknowledging that there are many ways to incorporate EBIPs. Within the CLUE implementations across different institutional settings, strategies have ranged from lecture-based courses with clicker questions to flipped courses in group-based active learning studio classrooms. We have not listed particular EBIPs as a critical component, because of this diversity, but what we do know from other work is that when scientific practices are incorporated into instruction, active learning techniques are almost always involved,[31,36] whereas the reverse is not necessarily true: that is, active learning does not necessarily mean engagement in scientific practices.

Opportunity to Explore without Penalty. *Definition.* A goal of the CLUE curriculum is to establish a classroom culture in which students feel comfortable exploring ideas without fear of not getting the "right" answer immediately. Across CLUE enactments, there are many spaces for students to "try on" different approaches to addressing problems and receive feedback on their efforts without losing points for "wrong answers". For example, homework administered on *beSocratic*[50,51] (which allows free-form drawing and writing) provides opportunities for students to further apply their knowledge through the use of scientific practices and self-assess their understanding of core chemistry ideas through assignments graded based on participation and effort, not correctness. In-class group problem solving and engagement with recitation and in-class worksheets from the curricular activity system further support students' exploration, understanding, and modifying ideas and are likewise graded on the basis of participation and effort. Therefore, while course examinations are graded for correctness, all other course activities are given credit for the "good faith effort".

Example. Opportunities for students to iteratively improve their explanations and models, in response to feedback from the instructor and peers, are intentionally built into the structure of the CLUE curricular materials. Typically, concepts in the curriculum are revisited multiple times throughout the year as well as within a single time point of the curriculum to provide students with various opportunities to revise and refine their ideas as student responses to homework and in-class problems are used to further drive instruction. For example, as part of the *electrostatic and bonding interactions* progression of ideas for how molecules interact through intermolecular forces, students are asked to work in small groups within the classroom to coconstruct knowledge with peers around drawing and writing explanations about how molecules might interact within different substances. Students would start with considering the polarity of H_2O molecules (content from a previous class) and how that would affect the way that water molecules interact, making water a liquid at room temperature. Then students would be asked to consider how the type and strength of interactions between CO_2 molecules differ and how those differences could explain why water is a liquid at room temperature while CO_2 is a gas. In large classes, these discussions are facilitated by the use of clicker questions or by each group drawing their responses on large whiteboards around the classroom so common ideas can be identified by the instructor and used to further drive instruction. These in-class ideas would then be followed up with a homework assignment in which students would be asked to explain properties of another set of substances (e.g., CH_3CH_2OH, CH_3OCH_3, and CH_3CH_3). Similar assessments in which students explain why ethanol has a higher boiling point than dimethyl ether have been previously published.[29,52] Discussion of how student homework responses are used at the beginning of the following class period to provide immediate formative feedback to students is described further below.

Implementation of Exploration without Penalty. This curriculum is meant to be implemented where the homework assignments, recitation, and in-class activities are all graded based on participation rather than correctness (i.e., credit for attending and attempting with a "good faith effort" instead of based on performance). This approach is designed to support a culture where students have opportunities to share their ideas and work together to build an understanding of content without competition around grading, while highlighting that learning can be a messy process where understanding comes from working with, and even struggling with, concepts to build connections. It also goes without saying that this curricular approach is not amenable to grading on a curve in which a predetermined percentage of students are given top grades.[53]

Characterizing the Fidelity of Implementation for Exploration without Penalty. The important idea behind this critical component is that students are not penalized for trying out ideas, while experiencing opportunities to reflect on and revise answers. Therefore, it would be important for an instructor who adopted CLUE to ensure that there is enough time for exploration without penalty. In addition to participation-based homework, points via student response systems (i.e., clickers) should also be based on participation rather than the percentage of questions answered correctly, as these questions are designed to elicit what students know before, during, and after instruction rather than to provide confirmation of learned concepts.

The percentage of course grades allocated to effort rather than correct responses and time allocated to student revisions of ideas within the learning space could provide a measure of the fidelity of implementation. In addition, students could be asked to complete a self-report survey examining elements of classroom climate, such as student comfort in exploring their own ideas or feeling they have a voice within the learning space. It has been shown that allocating more of the course grade to reward completion results in improvements in overall grade point average and a reduction in differences between different groups of students.[54] The relative weight of exploratory activities and other sorts of assessments would, of course, be something individual instructors could decide upon to fit their local environment.

Formative Feedback and Reflection. *Definition.* This approach, coupled with the critical component of exploration without penalty, means that a great deal of student time is spent in formative tasks from the curricular activity system. Whether it be on homework assignments, group in-class discussions, or activities in recitation sessions, students will likely not be fully correct the first time through; therefore, there must be mechanisms to provide feedback and

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

opportunities for reflection so that students eventually are guided to productive ideas. Such feedback can take various forms. For example, in large-enrollment classes, where individual feedback is not feasible, mechanisms include: 1) sequences of clicker questions where students are asked an initial question, then discuss with neighbors and revote; and 2) in-class review of homework via judicious selection of student responses of increasing sophistication. Students can be asked to identify what they see as differences among a set of anonymous answers that provide different depths of explanations.

Eliciting and valuing student ideas helps create a responsive, equitable classroom environment in which the instructor uses the student voices to drive instruction. It should be noted that these responses may be written explanations and arguments, drawings of structures or graphs, or calculations where the result is re-expressed in a different form. Each of these approaches requires that students reflect on and revise their responses where necessary, which we believe is an important aspect of feedback that is often omitted. Indeed, research shows that feedback mechanisms that "build in" the opportunity to reflect on the original response, are more successful than merely providing the correct answer.[55]

These approaches can be modified for different classes and instructional styles.

Example. Groups of students can be provided with a carefully chosen set of student responses (from a prior semester if needed) to a task. The group can be asked to construct a grading rubric and then use it to "grade" and provide feedback for the chosen responses. This activity essentially places the students in the role of an instructor and requires considerable reflection on their part.

Implementation of Formative Feedback and Reflection. Examples of student work presented should be representative of student responses with an emphasis on how responses can be improved, highlighting ideas that can be built upon and drawing student attention to difficult ideas and why they may have ideas that are problematic. Students can be asked "what are the positive aspects of this representation/explanation and what aspects could be improved?" Such an activity aligns with evaluating information from the scientific practice of *obtaining, evaluating, and communicating information*. Most CLUE instructors begin each class with a review of homework in this manner to provide students with feedback on their ideas. During this time, students can review their homework answers to help them recall what they submitted and how their work is similar to or different from the responses discussed in class.

Characterizing the Fidelity of Implementation of Formative Feedback and Reflection. The ways that the formative feedback and reflection component are implemented can be characterized by analysis of student materials, including in-class activities, homework, and recitation materials, to determine whether students are explicitly prompted to reflect upon their work. In addition, interviews with faculty regarding these ideas or recorded class sessions could provide additional evidence of formative feedback and reflection.

SUMMARY AND IMPLICATIONS

In this perspective, we have presented our approach to using the FOI framework as a guide to identify the critical components of the CLUE curriculum. We have defined five critical components, provided examples of each component, and, where appropriate, discussed how they might be assessed and how the fidelity of implementation could be characterized. To do this, we centralized the curricular activity system within CLUE (Figure 1) to help link together the structural components (what content critical components are essential to CLUE) to the instructional components (how content should be taught within the CLUE curriculum) as shown in Figure 3. That is, the curricular activity system provides an explicit and useful link between the structural categories that are concerned with how and why the curriculum was developed and the implementation categories that provide information about how the curriculum should be enacted. Our goal was to define those components that are critical to the implementation of CLUE and to provide guidance for those considering adopting this particular curriculum.

We also believe that this approach can be of assistance to others who are developing curricular materials and for those who are considering adopting new curricula of any kind. We note that when making curricular changes there is far more to consider than which textbook should be adopted. For example, adopters might consider 1) How and why is the curriculum sequenced in a particular way, and will reordering topics impact ideas introduced in another part of the curriculum? 2) Do the curricular materials fit together to provide a coherent approach to learning or can they be implemented separately on an ad-hoc basis? and 3) Does the way the course is enacted lend itself to a culture that supports students as they explore ideas and their own understanding without penalty, or does it employ approaches where students must get the correct answer—whether they can explain it or not?

Finally, we point out that while most of the effort to support transformation in STEM courses has focused on instructional practices such as active learning, peer groups, or in-class clickers (often referred to as Evidence Based Instructional Practices, EBIPs[10,56]), what often goes unrecognized is the impact of the design of the course, the sequence of instruction, how we elicit both what students know and how they should know it, and the messages we send by the course policies and practices. Our goal here is to provide a resource for both course designers and instructors who design, adopt, or adapt new curricula to help them consider what the critical components of such transformations are and how best they are communicated to the potential users.

ADVICE FOR FUTURE ADOPTERS AND ADAPTORS

It would not have been possible to identify the critical components for the CLUE curriculum if our project team had not been able to collect evidence over the years from multiple institutional implementations. Using this information, we provide advice for instructors who are considering adopting or adapting the CLUE curriculum. We recognize that most instructors will want to adapt the materials for their own situation, but our goal here is to emphasize that certain features should be maintained.

The overall flow of the curriculum (as described in the various structural components) was iteratively developed such that ideas introduced in one unit are further developed and expanded upon in a later unit. Therefore, switching the order of the content and materials would lose this coherence. However, the examples used within the context of the different topics can be easily modified to fit instructors' goals (e.g., connecting hydrogen bonding to base pair stability upon heating[57] or entropy to osmosis[58]). Additionally, having students use their knowledge (e.g., constructing models,

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

explanations, or arguments based on evidence) is vitally important to the development of deeper more useful knowledge structures and is also a more equitable approach than the traditional focus on calculations and facts.[31]

Similarly, it is important that adopters and adaptors of CLUE pay attention to the instructional critical components by providing students with the ability to explore without a penalty and periods of formative feedback with time for reflection. These instructional components contribute to a more equitable environment for all students to learn chemistry through a positive and supportive environment.

■ NEXT STEPS AND FUTURE WORK

The work presented here provides resources for future adopters and adaptors but also provides us, curriculum developers, and users with guidance about what might be most useful for the CLUE community and new users. For example, we plan to revise the instructors' materials to be far more explicit about how and why the curriculum is designed in this way and how and why the instructional materials are integrated. Indeed, this paper goes a long way to making these ideas, which previously might have been implicit, more visible. We hope that by explicitly stating what is critical and what is adaptable, new adopters will need less support to make the changes necessary. New materials (such as current research findings about the integration of mathematical sensemaking and mechanistic reasoning) will also be added to the repositories. All of these materials (including the original materials) will be made available to users as open education resources. We also hope that other curriculum developers will find this approach useful as they design and implement new courses.

■ ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available at https://pubs.acs.org/doi/10.1021/acs.jchemed.3c00190.

1) Preworkshop survey to identify the critical components for the curriculum, 2) More details about the week-long workshop, and 3) Common codes found from the team's preworkshop survey responses (PDF, DOCX)

■ AUTHOR INFORMATION

Corresponding Author

Sonia M. Underwood − *Department of Chemistry & Biochemistry and STEM Transformation Institute, Florida International University, Miami, Florida 33199, United States;* orcid.org/0000-0002-4919-2758; Email: Sonia.underwood@fiu.edu

Authors

Alex T. Kararo − *Department of Chemistry & Biochemistry and STEM Transformation Institute, Florida International University, Miami, Florida 33199, United States;* orcid.org/0000-0001-6788-9535

Lynmarie A. Posey − *Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, United States;* orcid.org/0000-0001-7713-0637

Amy M. Pollock − *Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, United States*

Deborah G. Herrington − *Department of Chemistry, Grand Valley State University, Allendale, Michigan 49401, United States;* orcid.org/0000-0001-6682-8466

Ryan L. Stowe − *Department of Chemistry, University of Wisconsin Madison, Madison, Wisconsin 53706, United States;* orcid.org/0000-0002-5548-495X

Justin H. Carmel − *Department of Chemistry & Biochemistry and STEM Transformation Institute, Florida International University, Miami, Florida 33199, United States;* orcid.org/0000-0001-9281-3751

Michael W. Klymkowsky − *Molecular, Cellular, and Developmental Biology, University of Colorado Boulder, Boulder, Colorado 80309, United States;* orcid.org/0000-0001-5816-9771

Melanie M. Cooper − *Department of Chemistry, Michigan State University, East Lansing, Michigan 48824, United States;* orcid.org/0000-0002-7050-8649

Complete contact information is available at: https://pubs.acs.org/10.1021/acs.jchemed.3c00190

Author Contributions

S.M.U. codeveloped idea of study, cocreated survey used within the workshop, co-organized and cofacilitated the workshop, assisted with the construction of critical components, and assisted with writing this paper. A.T.K. codeveloped idea of study, cocreated survey used within the workshop, analyzed data from survey, co-organized and cofacilitated the workshop, assisted with the construction of critical components, and assisted with writing this paper. L.A.P. responded to the survey, attended the entire workshop, assisted with the construction of critical components, and assisted with editing this paper. A.M.P. responded to the survey, attended the entire workshop, assisted with the construction of critical components, and assisted with editing this paper. D.G.H. responded to the survey, attended some of the workshop, assisted with the construction of critical components, and assisted with editing this paper. R.L.S. responded to the survey, attended some of the workshop, and assisted with writing this paper. J.H.C. attended some of the workshop and assisted with editing this paper. M.W.K. codeveloper of CLUE curriculum, responded to the survey, attended some of the workshop, and assisted with editing this paper. M.M.C. codeveloper of CLUE curriculum, responded to the survey, attended the entire workshop, assisted with the construction of critical components, and assisted with writing this paper.

Notes

The authors declare no competing financial interest.

■ ACKNOWLEDGMENTS

We would like to acknowledge the internal funding from startup funds at Florida International University (FIU) and the State of Florida for support through the STEM Transformation Institute at FIU with project UP:LIFT. In addition, we would like to thank all the instructors and institutions who have adopted the CLUE curriculum, which makes it possible for our research teams to learn more about the CLUE curriculum's impact on student success. Any opinions, findings, and conclusions or recommendations expressed in this article are from the authors and do not necessarily reflect the views of the funding sources.

■ REFERENCES

(1) Davis, E. A.; Janssen, F. J. J. M.; Van Driel, J. H. Teachers and Science Curriculum Materials: Where We Are and Where We Need to Go. *Studies in Science Education* **2016**, *52* (2), 127−160.

(2) Remillard, J. T. Examining Key Concepts in Research on Teachers' Use of Mathematics Curricula. *Review of Educational Research* **2005**, *75* (2), 211−246.

(3) Roschelle, J.; Knudsen, J.; Hegedus, S. From New Technological Infrastructures to Curricular Activity Systems: Advanced Designs for Teaching and Learning. In *Designs for Learning Environments of the Future: International Perspectives from the Learning Sciences*; Jacobson, M. J., Reimann, P., Eds.; Springer US: Boston, MA, 2010; pp 233−262. DOI: 10.1007/978-0-387-88279-6_9.

(4) Roschelle, J.; Pierson, J.; Empson, S.; Shechtman, N.; Dunn, M.; Tatar, D. Equity in Scaling up SimCalc: Investigating Differences in Student Learning and Classroom Implementation. *ICLS* **2010**, *1*, 333−340.

(5) Roschelle, J.; Shechtman, N.; Tatar, D.; Hegedus, S.; Hopkins, B.; Empson, S.; Knudsen, J.; Gallagher, L. P. Integration of Technology, Curriculum, and Professional Development for Advancing Middle School Mathematics: Three Large-Scale Studies. *American Educational Research Journal* **2010**, *47* (4), 833−878.

(6) Davis, E. A.; Krajcik, J. S. Designing Educative Curriculum Materials to Promote Teacher Learning. *Educational Researcher* **2005**, *34* (3), 3−14.

(7) Cooper, M. M.; Klymkowsky, M. W. Chemistry, Life, the Universe and Everything: A New Approach to General Chemistry, and a Model for Curriculum Reform. *Journal of Chemical Education* **2013**, *90*, 1116−1122.

(8) Stains, M.; Vickrey, T. Fidelity of Implementation: An Overlooked yet Critical Construct to Establish Effectiveness of Evidence-Based Instructional Practices. *CBE Life Science Education* **2017**, *16* (1), rm1.

(9) Century, J.; Rudnick, M.; Freeman, C. A Framework for Measuring Fidelity of Implementation: A Foundation for Shared Language and Accumulation of Knowledge. *American Journal of Evaluation* **2010**, *31* (2), 199−218.

(10) Stains, M.; Harshman, J.; Barker, M. K.; Chasteen, S. V.; Cole, R. S.; DeChenne-Peters, S. E.; Eagan, M. K.; Esson, J. M.; Knight, J. K.; Laski, F. A.; Levis-Fitzgerald, M.; Lee, C. J.; Lo, S. M.; McDonnell, L. M.; McKay, T. A.; Michelotti, N.; Musgrove, A.; Palmer, M. S.; Plank, K. M.; Rodela, T. M.; Sanders, E. R.; Schimpf, N. G.; Schulte, P. M.; Smith, M. K.; Stetzer, M.; Van Valkenburgh, B.; Vinson, E.; Weir, L. K.; Wendel, P. J.; Wheeler, L. B.; Young, A. M. Anatomy of STEM Teaching in North American Universities. *Science* **2018**, *359* (6383), 1468−1470.

(11) Laverty, J. T.; Underwood, S. M.; Matz, R. L.; Posey, L. A.; Carmel, J. H.; Caballero, M. D.; Fata-Hartley, C. L.; Ebert-May, D.; Jardeleza, S. E.; Cooper, M. M. Characterizing College Science Assessments: The Three-Dimensional Learning Assessment Protocol. *PLoS One* **2016**, *11* (9), No. e0162333.

(12) Cooper, M. M.; Posey, L. A.; Underwood, S. M. Core Ideas and Topics: Building up or Drilling Down? *Journal of Chemical Education* **2017**, *94* (5), 541−548.

(13) Underwood, S. M.; Kararo, A. T. Design Based Implementation Research (DBIR): An Approach to Propagating a Transformed General Chemistry Curriculum across Multiple Institutions. *Journal of Chemical Education* **2021**, *98* (12), 3643−3655.

(14) Anderson, C. W.; de los Santos, E. X.; Bodbyl, S.; Covitt, B. A.; Edwards, K. D.; Hancock, J. B.; Lin, Q.; Thomas, C. M.; Penuel, W. R.; Welch, M. M. Designing Educational Systems to Support Enactment of the Next Generation Science Standards. *Journal of Research In Science Teaching* **2018**, *55* (7), 1026−1052.

(15) Cooper, M. M.; Klymkowsky, M. W. *CLUE: Chemistry, Life, the Universe and Everything*. https://openbooks.lib.msu.edu/clue/ (accessed Mar. 7, 2023).

(16) Biggs, J. Enhancing Teaching through Constructive Alignment. *High Education* **1996**, *32* (3), 347−364.

(17) Brown, A. L. Design Experiments: Theoretical and Methodological Challenges in Creating Complex Interventions in Classroom Settings. *Journal of the Learning Sciences* **1992**, *2* (2), 141−178.

(18) Klymkowsky, M. W.; Rentsch, J. D.; Begovic, E.; Cooper, M. M. The Design and Transformation of Biofundamentals: A Nonsurvey Introductory Evolutionary and Molecular Biology Course. *CBE Life Science Education* **2016**, *15* (4), ar70.

(19) Cooper, M. M.; Stowe, R. L.; Crandell, O. M.; Klymkowsky, M. W. Organic Chemistry, Life, the Universe and Everything (OCLUE): A Transformed Organic Chemistry Curriculum. *Journal of Chemical Education* **2019**, *96* (9), 1858−1872.

(20) O'Donnell, C. L. Defining, Conceptualizing, and Measuring Fidelity of Implementation and Its Relationship to Outcomes in K-12 Curriculum Intervention Research. *Review of Educational Research* **2008**, *78* (1), 33−84.

(21) Hall, G. E.; Hord, S. M. *Change in Schools: Facilitating the Process. SUNY Series in Educational Leadership*; State University of New York Press: Albany, NY, 1987.

(22) Becker, D. R.; Smith, J.; Tanzman, B.; Drake, R. E.; Tremblay, T. Fidelity of Supported Employment Programs and Employment Outcomes. *Psychiatric Services* **2001**, *52* (6), 834−836.

(23) Neale, D. C.; Smith, D.; Johnson, V. G. Implementing Conceptual Change Teaching in Primary Science. *Elementary School Journal* **1990**, *91* (2), 109−131.

(24) Goudreau Collison, C.; Newman, D. L.; Biehler, J. Q.; Nelson, M.; O'Brien Daly, P.; Jackson, M.; Isaac, C.; Tebrugge, M.; Anderson, J.; Edelbach, B.; Tusch, D.; Cody, J. A. Reformed Experimental Activities (REActivities): Gauging the Fidelity of Implementation in a Reformed Undergraduate Organic Chemistry Laboratory. *Journal of Chemical Education* **2022**, *99* (5), 2032−2043.

(25) National Research Council. *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas*; National Academies Press: Washington, DC, 2012.

(26) Noyes, K.; Cooper, M. M. Investigating Student Understanding of London Dispersion Forces: A Longitudinal Study. *Journal of Chemical Education* **2019**, *96* (9), 1821−1832.

(27) Cooper, M. M.; Kouyoumdjian, H.; Underwood, S. M. Investigating Students' Reasoning about Acid-Base Reactions. *Journal of Chemical Education* **2016**, *93* (10), 1703−1712.

(28) Cooper, M. M.; Underwood, S. M.; Hilley, C. Z. Development and Validation of the Implicit Information from Lewis Structures Instrument (IILSI): Do Students Connect Structures with Properties? *Chemistry Education Research and Practice* **2012**, *13* (3), 195−200.

(29) Kararo, A. T.; Colvin, R. A.; Cooper, M. M.; Underwood, S. M. Making Predictions and Constructing Explanations: An Investigation into Introductory Chemistry Students' Understanding of Structure-Property Relationships. *Chemistry Education Research and Practice* **2019**, *20* (1), 316−328.

(30) Krist, C.; Schwarz, C. V.; Reiser, B. J. Identifying Essential Epistemic Heuristics for Guiding Mechanistic Reasoning in Science Learning. *Journal of the Learning Sciences* **2019**, *28* (2), 160−205.

(31) Ralph, V. R.; Scharlott, L. J.; Schafer, A. G.; Deshaye, M. Y.; Becker, N. M.; Stowe, R. L. Advancing Equity in STEM: The Impact Assessment Design Has on Who Succeeds in Undergraduate Introductory Chemistry. *JACS Au* **2022**, *2* (8), 1869−1880.

(32) Russ, R. S.; Scherr, R. E.; Hammer, D.; Mikeska, J. Recognizing Mechanistic Reasoning in Student Scientific Inquiry: A Framework for Discourse Analysis Developed from Philosophy of Science. *Science Education* **2008**, *92* (3), 499−525.

(33) Williams, L. C.; Underwood, S. M.; Klymkowsky, M. W.; Cooper, M. M. Are Noncovalent Interactions an Achilles Heel in Chemistry Education? A Comparison of Instructional Approaches. *Journal of Chemical Eduation.* **2015**, *92* (12), 1979−1987.

(34) Crandell, O. M.; Kouyoumdjian, H.; Underwood, S. M.; Cooper, M. M. Reasoning about Reactions in Organic Chemistry: Starting It in General Chemistry. *Journal of Chemical Education* **2019**, *96* (2), 213−226.

(35) Noyes, K.; Carlson, C. G.; Stoltzfus, J. R.; Schwarz, C. V.; Long, T. M.; Cooper, M. M. A Deep Look into Designing a Task and

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385

Coding Scheme through the Lens of Causal Mechanistic Reasoning. *Journal of Chemical Education* **2022**, *99* (2), 874−885.

(36) Ralph, V. R.; Scharlott, L. J.; Schwarz, C. E.; Becker, N. M.; Stowe, R. L. Beyond Instructional Practices: Characterizing Learning Environments That Support Students in Explaining Chemical Phenomena. *Journal of Research in Science Teaching* **2022**, *59* (5), 841−875.

(37) Talanquer, V. Exploring Mechanistic Reasoning in Chemistry. In *Science Education Research and Practice in Asia-Pacific and Beyond*; Yeo, J., Teo, T. W., Tang, K.-S., Eds.; Springer Singapore: Singapore, 2018; pp 39−52, DOI: 10.1007/978-981-10-5149-4_3.

(38) Caspari, I.; Kranz, D.; Graulich, N. Resolving the Complexity of Organic Chemistry Students' Reasoning through the Lens of a Mechanistic Framework. *Chemistry Education Research and Practice* **2018**, *19* (4), 1117−1141.

(39) Becker, N. M.; Noyes, K.; Cooper, M. M. Characterizing Students' Mechanistic Reasoning about London Dispersion Forces. *Journal of Chemical Education* **2016**, *93* (10), 1713−1724.

(40) Cooper, M. M.; Grove, N.; Underwood, S. M.; Klymkowsky, M. W. Lost in Lewis Structures: An Investigation of Student Difficulties in Developing Representational Competence. *Journal of Chemical Education* **2010**, *87* (8), 869−874.

(41) Stowe, R. L.; Esselman, B. J. The Picture Is Not the Point: Toward Using Representations as Models for Making Sense of Phenomena. *Journal of Chemical Education* **2023**, *100* (1), 15−21.

(42) Cooper, M. M.; Underwood, S. M.; Hilley, C. Z.; Klymkowsky, M. W. Development and Assessment of a Molecular Structure and Properties Learning Progression. *Journal of Chemical Education* **2012**, *89* (11), 1351−1357.

(43) Underwood, S. M.; Reyes-Gastelum, D.; Cooper, M. M. When Do Students Recognize Relationships between Molecular Structure and Properties? A Longitudinal Comparison of the Impact of Traditional and Transformed Curricula. *Chemistry Education Research and Practice* **2016**, *17* (2), 365−380.

(44) Underwood, S. M.; Posey, L. A.; Herrington, D. G.; Carmel, J. H.; Cooper, M. M. Adapting Assessment Tasks To Support Three-Dimensional Learning. *Journal of Chemical Education* **2018**, *95* (2), 207−217.

(45) Bain, K.; Bender, L.; Bergeron, P.; Caballero, M. D.; Carmel, J. H.; Duffy, E. M.; Ebert-May, D.; Fata-Hartley, C. L.; Herrington, D. G.; Laverty, J. T.; Matz, R. L.; Nelson, P. C.; Posey, L. A.; Stoltzfus, J. R.; Stowe, R. L.; Sweeder, R. D.; Tessmer, S. H.; Underwood, S. M.; Urban-Lurain, M.; Cooper, M. M. Characterizing College Science Instruction: The Three-Dimensional Learning Observation Protocol. *PLoS One* **2020**, *15* (6), No. e0234640.

(46) Matz, R. L.; Fata-Hartley, C. L.; Posey, L. A.; Laverty, J. T.; Underwood, S. M.; Carmel, J. H.; Herrington, D. G.; Stowe, R. L.; Caballero, M. D.; Ebert-May, D.; Cooper, M. M. Evaluating the Extent of a Large-Scale Transformation in Gateway Science Courses. *Science Advances* **2018**, *4* (10), No. eaau0554.

(47) Dancy, M.; Henderson, C.; Apkarian, N.; Johnson, E.; Stains, M.; Raker, J. R.; Lau, A. Physics Instructors Knowledge and Use of Active Learning Has Increased over the Last Decade but Most Still Lecture Too Much. *arXiv (Physics Education)*, November 23, 2022, ver. 1. DOI: 10.48550/arXiv.2211.13082.

(48) Yik, B. J.; Raker, J. R.; Apkarian, N.; Stains, M.; Henderson, C.; Dancy, M. H.; Johnson, E. Evaluating the Impact of Malleable Factors on Percent Time Lecturing in Gateway Chemistry, Mathematics, and Physics Courses. *International Journal of STEM Education* **2022**, *9* (1), 15.

(49) Lund, T. J.; Stains, M. The Importance of Context: An Exploration of Factors Influencing the Adoption of Student-Centered Teaching among Chemistry, Biology, and Physics Faculty. *International Journal of STEM Education* **2015**, *2* (1), 13−34.

(50) Bryfczynski, S. P. *BeSocratic: An Intelligent Tutoring System for the Recognition, Evaluation, and Analysis of Free-Form Student Input*. Ph.D. Thesis, Clemson University, 2012.

(51) Cooper, M. M.; Underwood, S. M.; Bryfczynski, S. P.; Klymkowsky, M. W. A Short History of the Use of Technology to Model and Analyze Student Data for Teaching and Research. In *Tools of Chemistry Education Research*; Cole, R. S., Bunce, D., Eds.; ACS Symposium Series; American Chemical Society: Washington, D.C., 2014; pp 219−239.

(52) Underwood, S. M.; Kararo, A. T.; Gadia, G. Investigating the Impact of Three-Dimensional Learning on Student Understanding of Structure-Property Relationships. *Chemistry Education Research and Practice* **2021**, *22*, 247−262.

(53) Bowen, R. S.; Cooper, M. M. Grading on a Curve as a Systemic Issue of Equity in Chemistry Education. *Journal of Chemical Education* **2022**, *99* (1), 185−194.

(54) Tashiro, J.; Talanquer, V. Exploring Inequities in a Traditional and a Reformed General Chemistry Course. *Journal of Chemical Education* **2021**, *98* (12), 3680−3692.

(55) Carless, D.; Boud, D. The Development of Student Feedback Literacy: Enabling Uptake of Feedback. *Assessment & Evaluation in Higher Education* **2018**, *43* (8), 1315−1325.

(56) Freeman, S.; Eddy, S. L.; McDonough, M.; Smith, M. K.; Okoroafor, N.; Jordt, H.; Wenderoth, M. P. Active Learning Increases Student Performance in Science, Engineering, and Mathematics. *PNAS* **2014**, *111* (23), 8410−8415.

(57) Roche Allred, Z. D.; Farias, A. J.; Kararo, A. T.; Parent, K. N.; Matz, R. L.; Underwood, S. M. Students' Use of Chemistry Core Ideas to Explain the Structure and Stability of DNA. *Biochemistry and Molecular Biology Education* **2021**, *49* (1), 55−68.

(58) Martinez, B. L.; Kararo, A. T.; Parent, K. N.; Underwood, S. M.; Matz, R. L. Creating and Testing an Activity of Interdisciplinary Connections: Entropy to Osmosis. *Chemistry Education Research and Practice* **2021**, *22*, 683.

https://doi.org/10.1021/acs.jchemed.3c00190
J. Chem. Educ. 2023, 100, 3374−3385